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RESEARCH MEMORANDUM

ANALYSES FOR TURBOJET THRUST AUGMENTATION WITH FUEL-RICH AFTERBURNING OF HYDROGEN, DIBORANE, AND HYDRAZINE

By James F. Morris

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This [redacted] person is prohibited by law.

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON

June 18, 1957

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

ANALYSES FOR TURBOJET THRUST AUGMENTATION WITH FUEL-RICH AFTERBURNING OF HYDROGEN, DIBORANE, AND HYDRAZINE

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SUMMARY

Turbojet-engine net thrusts augmented with fuel-rich afterburning during takeoff and flight were computed. When compared at equal liquid weights, hydrogen, diborane, or hydrazine, burned at higher than stoichiometric fuel-air ratios, can produce thrusts that are, to some limit, greater than those for a 220-second specific-impulse rocket combined with stoichiometric afterburning of the turbojet fuel. At the conditions analyzed, this limit for liquid hydrogen is a liquid-air ratio of 0.16; the corresponding thrust is 27 percent greater than that for stoichiometric afterburning alone.

Fuel-rich afterburning of 700° K hydrogen can yield augmented thrusts greater than those for stoichiometric combustion of 700° K hydrogen and 400° K air augmented with a 321.6-second specific-impulse rocket.

INTRODUCTION

Turbojet-propelled aircraft can take off with heavier loads and fly at higher speeds if thrust is augmented. Afterburners and rockets are often used for this purpose. Afterburning is generally limited to near-stoichiometric fuel-air ratios because hydrocarbon-rich combustion offers only slight thrust gains. However, rich afterburning may be practical with some of the fuels being considered for future aircraft use. Hydrogen and diborane are among the fuels that can increase flight range and altitude. Rich combustion of these fuels may produce high values of augmented thrust.

If fuel-rich afterburning is effective, it will be a simple method for increasing turbojet-engine thrust. Rich combustion should require, at most, a second afterburner fuel system and an exhaust nozzle capable of larger area changes.

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Reference 1 shows that thrust increases with diborane flow up to a fuel-air ratio of 1.3 times the stoichiometric value; the rate of change of thrust with fuel-air ratio at the stoichiometric point indicates that hydrogen-rich afterburning will also augment thrust. Further, reference 1 confirms the futility of rich combustion with hydrocarbons.

The ideal fuel for rich afterburning would be a dense one with a high heat of combustion. It would decompose when heated, releasing energy and forming low-molecular-weight products. Hydrazine is a fairly dense liquid that has a positive heat of formation and yields products with low molecular weights. These properties make hydrazine a good prospect for fuel-rich afterburning even though it has a low heat of combustion. 4483

This report presents net thrusts computed for hydrogen, diborane, and hydrazine with fuel-air ratios from stoichiometric values to 0.5. Net thrusts for fuel-rich afterburning are compared with those for stoichiometric combustion of the turbojet fuel and air augmented with a 220-second specific-impulse rocket. Conditions were selected to represent fuel-rich afterburning during

(1) Takeoff with any of four turbojet engines having compressor pressure ratios from 5.2 to 12 and turbine-outlet total temperatures from 1510° to 2062° R

(2) Flight at Mach 2 and an altitude of 55,000 feet with a turbojet engine having a compressor pressure ratio of 8.4 and a turbine-outlet total temperature of 2062° R (sea-level-static ratings).

These turbojet engines are described in reference 2. Three of the engines are similar to existing models; the turbojet engine with a 2062° R turbine-outlet temperature is an advanced design with a cooled turbine (engine D of table I).

ANALYTICAL METHODS

The conditions and fuels for these studies were selected to represent takeoff and flight of turbojet engines with fuel-rich afterburning. Some afterburner-inlet conditions for various turbojet-engine operating points are given in table I, which was taken from reference 2. The results of this work extend those of reference 2.

Fuels and Operating Conditions

Net thrusts and exhaust-nozzle-exit areas were computed for fuel-rich combustion of the following liquids: hydrogen at 20.39° K, diborane at 180.63° K, and hydrazine at 298.16° K. The conditions chosen for these studies are

[redacted]

(1) Takeoff with an engine-inlet-air temperature of 298° K, an afterburner pressure of 2 atmospheres, and an exhaust-nozzle pressure ratio of 2 (complete expansion)

(2) Flight at Mach 2 and an altitude of about 55,000 feet with an engine-inlet-air temperature of 400° K, an afterburner pressure of 1 atmosphere, and exhaust-nozzle pressure ratios of 2, 6, and 11. The pressure ratio of 11 gives complete expansion.

The calculations were made for fuel-air ratios ranging from stoichiometric values to 0.5. For hydrogen and diborane, it was assumed that the fuel being considered was used in the primary combustors and the afterburners. However, the low heat of combustion for hydrazine, about 7170 Btu per pound, requires a different approach. Therefore, for hydrazine, it was assumed that hydrogen was burned in the primary combustors and the afterburners of turbojet engines for fuel-air ratios up to the stoichiometric point. Above this point, hydrazine was added; the fuel-air ratio for hydrazine is given by the over-all fuel-air ratio minus 0.0293. This method gives low fuel flows for normal turbojet operation.

If fuels were heated by sources external to the engine, higher net thrusts would result. To indicate this effect, net thrusts were computed for 700° K hydrogen burned with 400° K engine-inlet air. A combustion pressure of 1 atmosphere and an exhaust-nozzle pressure ratio of 11 (complete expansion) were used.

The results for fuel-rich afterburning are compared with net thrusts for stoichiometric combustion of the turbojet fuel and air augmented with a 220-second specific-impulse rocket.

Thermodynamic Data

Thermodynamic data from references 3, 4(table III), and 5 were used in the calculations. The combustion products for hydrogen and hydrazine were assumed to be the following gases in equilibrium at the combustion temperature: H_2, H_2O, N_2, NO, O_2, OH, H, N, and O. Unpublished data for hydrogen indicate that at a combustion temperature of 2000° K about 99 percent of the total enthalpy is required for the nondissociated products. As the combustion temperature decreases, this percentage increases. Therefore, the products for hydrogen and hydrazine at combustion temperatures below 2000° K were assumed to be H_2, H_2O, and N_2 gases.

For diborane, the following combustion products were assumed to be in equilibrium for all combustion temperatures: BH, BO, B_2O_3, H_2, H_2O, N_2, NO, O_2, OH, H, N, O, and B gases and B_2O_3 liquid. The products B_2O_2

(ref. 6) and HBO_2 (ref. 7) should be present also, but complete, consistent thermodynamic data for these species are not available, and, therefore, these data were not included.

Calculation Methods

The turbojet engine with afterburner was assumed to be an adiabatic system. Calculations could then be made as if the primary and afterburner fuels and air, all at their engine-inlet conditions, were burned in one process to yield the equilibrium composition and temperature at the afterburner pressure. 4483

Afterburner combustion temperatures and compositions were determined using the equilibrium relations for the selected products and the following expression:

$$(\Sigma n_i H^{\circ}_{T,i})_{f+a} = (\Sigma n_i H^{\circ}_{T,i})_{EP,T_c,p_c}$$

That is, the sum of the enthalpies of the equilibrium products at the afterburner combustion temperature and pressure is equal to the sum of the enthalpies of the reactants at their engine-inlet temperatures.

An isentropic expansion of the combustion products was assumed to occur with frozen composition governed by the entropy relation

$$\Delta S^{\circ}_T = \left\{\Sigma n_i \left[(S^{\circ}_T)_e - (S^{\circ}_T)_c\right]\right\}_{EP} = (\Sigma n_i)_{EP,g} R \ln \frac{p_e}{p_c}$$

With this equation, the exhaust-nozzle-exit temperature was obtained, and the enthalpy change for the expansion was calculated as follows:

$$\Delta H^{\circ}_T = \left\{\Sigma n_i \left[(H^{\circ}_T)_e - (H^{\circ}_T)_c\right]_i\right\}_{EP}$$

Then, the stream momentum and area at the exhaust-nozzle exit and the net thrust were computed by using the following expressions:

$$m = \left(1 + \frac{f}{a}\right) \frac{V_e}{g} = \left(1 + \frac{f}{a}\right) \sqrt{\frac{2J(-\Delta H^{\circ}_T)}{g(\Sigma n_i M_i)_{EP}}}$$

$$A_e = \frac{\left(1 + \frac{f}{a}\right) RT_e}{p_e M_e V_e} = \frac{\left(1 + \frac{f}{a}\right)^2 RT_e (\Sigma n_i)_{EP}}{g p_e m (\Sigma n_i M_i)_{EP}}$$

$$F_n = m + A_e(p_e - p_{am}) - \frac{V_{am}}{g}$$

Free-stream momentums (V_{am}/g) of 0 and 61 pounds of thrust per pound of air per second were used in the calculations for 298.16° and 400° K inlet-air temperatures, respectively.

Air Specific Impulse

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Air specific impulse can be calculated using values for an exhaust-nozzle pressure ratio of 2 in the following expression:

$$S_a = \left(F_n + p_{am}A_e + \frac{V_{am}}{g}\right)_{p_c/p_e = 2}$$

Errors of about 0.5 percent will result (ref. 1).

RESULTS AND DISCUSSION

Net thrusts were computed for fuel-rich afterburning of hydrogen, diborane, and hydrazine. These thrusts are compared with results for stoichiometric combustion of the turbojet fuel and air augmented with a 220-second specific-impulse rocket. In all the figures, solid-line curves show net thrusts and exhaust-nozzle-exit areas for fuel-rich afterburning. The broken lines give net-thrust values for the rocket method.

Takeoff Thrust Augmentation

The results shown in figure 1 represent sea-level-static thrust augmentation for any of the four turbojet engines of table I. The assigned exhaust-nozzle pressure ratio of 2 gives complete expansion for afterburner combustion products. For this case, net-thrust and exit-area values are very close to those for a choked, convergent exhaust nozzle.

Figure 1(a) relates net thrust, exhaust-nozzle-exit area, and liquid-air ratio for fuel-rich afterburning with 20.39° K liquid hydrogen and 298.16° K air. Hydrogen can produce net thrusts higher than those of the rocket method for over-all liquid-air ratios from the stoichiometric point (0.0293) to 0.1. Results for hydrogen-air ratios of 0.0293, 0.1, 0.25, and 0.5 are given in the following table.

[redacted]

Hydrogen-air ratio	Net thrust		Exhaust-nozzle-exit area	
	lb thrust / (lb air/sec)	percent increase	sq ft / (lb air/sec)	percent increase
0.0293	104	0	0.0352	0
.1	120	15.4	.0376	6.8
.25	132	26.9	.0414	17.6
.5	149	43.3	.0456	29.6

Figure 1(b) indicates that fuel-rich combustion of 180.63° K liquid diborane and 298.16° K air can yield net thrusts about equal to those of the rocket method for liquid-air ratios from the stoichiometric point (0.067) to 0.09. The following table presents net-thrust and nozzle-exit-area values for diborane-air ratios of 0.067, 0.09, and 0.25: 4483

Diborane-air ratio	Net thrust		Exhaust-nozzle-exit area	
	lb thrust / (lb air/sec)	percent increase	sq ft / (lb air/sec)	percent increase
0.067	109	0	0.0349	0
.09	114	4.6	.0363	4
.25	123	12.8	.0394	12.9

Figure 1(c) shows variations of net thrust and exhaust-nozzle-exit area with liquid-air ratio for combustion of 298.16° K hydrazine with a stoichiometric mixture of 20.39° K liquid hydrogen and 298.16° K air. In this case, fuel-rich afterburning can produce augmented thrusts slightly higher than those of the rocket method for liquid-air ratios from 0.0293 to 0.07. Results for fuel-rich afterburning at liquid-air ratios of 0.0293, 0.07, 0.25, and 0.5 are presented in the following table:

Hydrazine-air ratio plus 0.0293	Net thrust		Exhaust-nozzle-exit area	
	lb thrust / (lb air/sec)	percent increase	sq ft / (lb air/sec)	percent increase
0.0293	104	0	0.0352	0
.07	113	8.7	.0358	1.7
.25	132.5	27.4	.0418	18.8
.5	158	52.0	.0495	40.6

Then, for takeoff with turbojet afterburning, the results show that based on liquid weight:

(1) Fuel-rich combustion of liquid hydrogen gives the highest net thrusts of the methods considered for liquid-air ratios up to 0.1.

[redacted]

(2) The 220-second specific-impulse rocket is the best method at liquid-air ratios above 0.1.

(3) Hydrogen is the most effective rich-afterburning method for liquid-air ratios up to 0.24.

(4) At fuel-air ratios greater than 0.24 hydrazine, burned with a stoichiometric mixture of hydrogen and air, yields higher net thrusts than rich combustion of hydrogen alone. The slope of the curve for the hydrazine method used at liquid-air ratios greater than 0.24 is about 102 pounds of thrust per pound of fuel per second.

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Flight Thrust Augmentation

Results computed for fuel-rich afterburning used during flight with a turbojet engine having a cooled turbine are given in figures 2 and 3. In these figures, variations of net thrust and exhaust-nozzle-exit area with liquid-air ratio and exhaust-nozzle pressure ratio are shown.

The conditions selected for these studies correspond to flight at Mach 2 and an altitude of about 55,000 feet with engine D of table I. An engine-inlet-air temperature of 400° K, an afterburner pressure of 1 atmosphere, and exhaust-nozzle pressure ratios of 2, 6, and 11 were assumed. Again, the nozzle pressure ratio of 2 gives results very close to those for a choked, convergent exhaust nozzle or for the throat of a convergent-divergent exhaust nozzle. The pressure ratio of 11 represents complete expansion of exhaust products.

Figure 2(a) reveals that fuel-rich afterburning of liquid hydrogen can produce net thrusts larger than those for the rocket method for liquid-air ratios from 0.0293 to 0.16. This increase occurs for exhaust-nozzle pressure ratio of 2, 6, and 11. In the following tables, results for hydrogen-air ratios of 0.0293, 0.16, 0.25, and 0.5 are given:

Hydrogen-air ratio	Exhaust-nozzle pressure ratio					
	2		6		11	
	Net thrust					
	lb thrust / (lb air/sec)	percent increase	lb thrust / (lb air/sec)	percent increase	lb thrust / (lb air/sec)	percent increase
0.0293	106	0	120	0	123	0
.16	135	27.4	149	24.2	152	23.6
.25	145.5	37.2	160	33.3	163	32.5
.5	169	59.5	185	54.1	188	52.9

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Hydrogen-air ratio	Exhaust-nozzle pressure ratio					
	2		6		11	
	Exhaust-nozzle-exit area					
	sq ft / (lb air/sec)	percent increase	sq ft / (lb air/sec)	percent increase	sq ft / (lb air/sec)	percent increase
0.0293	0.069	0	0.107	0	0.154	0
.16	.079	14.5	.119	11.2	.166	7.8
.25	.084	21.7	.124	15.9	.173	12.3
.5	.093	34.8	.137	28.0	.189	22.7

Figure 2(b) shows that values of net thrust for the fuel-rich combustion of liquid diborane and 400° K air are greater than those of the rocket method for liquid-air ratios from 0.067 to 0.13. Results for diborane-air ratios of 0.067, 0.13, and 0.25 are listed in the following tables:

Diborane-air ratio	Exhaust-nozzle pressure ratio					
	2		6		11	
	Net thrust					
	lb thrust / (lb air/sec)	percent increase	lb thrust / (lb air/sec)	percent increase	lb thrust / (lb air/sec)	percent increase
0.067	108	0	123	0	126	0
.13	120.5	11.6	136	10.6	139.5	10.7
.25	129	19.4	146	18.7	149.5	18.6

Dibroane-air ratio	Exhaust-nozzle pressure ratio					
	2		6		11	
	Exhaust-nozzle-exit area					
	sq ft / (lb air/sec)	percent increase	sq ft / (lb air/sec)	percent increase	sq ft / (lb air/sec)	percent increase
0.067	0.069	0	0.109	0	0.158	0
.13	.074	7.2	.117	7.3	.168	6.3
.25	.078	13.0	.124	13.8	.180	13.9

Figure 2(c) indicates that combustion of hydrazine with a stoichiometric mixture of liquid hydrogen and 400° K air is a less effective method than the 220-second specific-impulse rocket. Net thrusts between fuel-air ratios of 0.0293 and 0.25 for the hydrazine method with nozzle pressure ratios of 2, 6, and 11 are about equal to those that would result

for 182-, 195-, and 198-second rockets, respectively, used to augment stoichiometric combustion of hydrogen. In the following tables, results are given for liquid-air ratios of 0.0293, 0.25, and 0.5:

Hydrazine-air ratio plus 0.0293	Exhaust-nozzle pressure ratio					
	2		6		11	
	Net thrust					
	lb thrust / (lb air/sec)	percent increase	lb thrust / (lb air/sec)	percent increase	lb thrust / (lb air/sec)	percent increase
0.0293	106	0	120	0	123	0
.25	146	37.7	163	35.8	166.5	35.4
.5	185	74.5	204.5	70.4	209	69.9

Figure 3 shows results for 700° K hydrogen and 400° K engine-inlet air. The fuel must be heated by sources external to the turbojet engine if thrust is to be increased. In the present case, little 700° K hydrogen would be available. This high temperature was selected in order to magnify the effects for fuel-rich afterburning of heated hydrogen and to indicate gains for hydrogen where cooling of large heat sources is required. A straight line for the separate, complete expansion of the hydrogen at 700° K in excess of the stoichiometric amount is also given. This line is the same as one that would result for the rocket method using a 321.6-second specific-impulse rocket. The curve for rich combustion of 700° K hydrogen approaches a straight line parallel to and about 30 pounds of thrust per pound of air per second higher than the line for a 321.6-second rocket.

Results for fuel-rich combustion at hydrogen-air ratios of 0.0293, 0.1, 0.25, and 0.5 are presented in the table that follows:

Hydrazine-air ratio plus 0.0293	Exhaust-nozzle pressure ratio					
	2		6		11	
	Exhaust-nozzle-exit area					
	sq ft / (lb air/sec)	percent increase	sq ft / (lb air/sec)	percent increase	sq ft / (lb air/sec)	percent increase
0.0293	0.069	0	0.107	0	0.154	0
.25	.084	21.7	.130	21.5	.186	20.8
.5	.100	44.9	.153	43.0	.216	40.2

[redacted]

Hydrogen-air ratio	Net thrust		Exhaust-nozzle-exit area	
	lb thrust / (lb air/sec)	percent increase	sq ft / (lb air/sec)	percent increase
0.0293	127	0	0.157	0
.1	166	30.7	.182	15.9
.25	222	74.8	.221	40.7
.5	308	142.5	.284	80.9

For Mach 2 flight at 55,000 feet using turbojet engine D with afterburning of liquid fuels, the results show that on a weight basis:

(1) Hydrogen-rich combustion gives net thrusts higher than those of the other three methods studied for liquid-air ratios up to 0.16.

(2) At liquid-air ratios above 0.16, the rocket is the best of the methods.

(3) Between liquid-air ratios of 0.0293 and 0.25, complete expansion of the products of hydrazine added to a stoichiometric mixture of hydrogen and air yields net thrusts equal to those for a 198-second specific-impulse rocket combined with stoichiometric afterburning of hydrogen and air.

(4) At liquid-air ratios greater than 0.205, 0.215, and 0.245 for nozzle pressure ratios of 11, 6, and 2, respectively, the most effective fuel-rich afterburning method is hydrazine addition to a stoichiometric mixture of hydrogen and air.

For the same flight conditions rich combustion of hot hydrogen was examined. Complete expansion from 1 to 0.0909 atmosphere of 700° K hydrogen alone produces net thrusts equal to those of a 321.6-second specific-impulse rocket. In order to increase the thrust of the turbojet engine, the hydrogen must be heated by external sources. Fuel-rich afterburning of 700° K hydrogen could then yield net thrusts greater by 30 pounds per pound of air per second then those for stoichiometric combustion of 700° K hydrogen and 400° K air augmented with a 321.6-second rocket.

Fuel-rich afterburning of hydrogen, hydrazine, or diborane can produce high values of augmented thrust. On a weight basis, hydrogen is very effective. However, the specific gravity of liquid hydrogen is 0.07 as compared with 0.447 for liquid diborane and 1.011 for hydrazine. Whenever volume is critical, fuel-rich combustion with hydrazine should be considered.

Exhaust-nozzle-exit areas are given to show the amount of area change required for the fuel-rich-afterburning methods. High net-thrust values

demand large exhaust-nozzle-area changes. Afterburning at fuel-air ratios considerably greater than stoichiometric would also require an additional afterburner fuel system. In this manner, one afterburner fuel system could be used for efficient operation at fuel-air ratios up to the stoichiometric point. The other fuel system would be used only during rich afterburning. No changes in the afterburner fuel system and exhaust nozzle would be needed if fuel-rich afterburning was used to obtain only small thrust gains.

CONCLUDING REMARKS

Fuel-rich afterburning of hydrogen, hydrazine, or diborane can be used to augment turbojet-engine thrusts during takeoff and flight. At equal liquid weights, rich combustion of these fuels can produce thrusts that are to some limit greater than those for stoichiometric afterburning of the turbojet fuel and air augmented with a 220-second specific-impulse rocket. For liquid hydrogen and the conditions selected for these calculations, this limit is a liquid-air ratio of 0.16; corresponding net thrusts are as much as 27 percent larger than those for stoichiometric afterburning alone.

Fuel-rich afterburning may be simpler and more economical than the rocket method of thrust augmentation. In flight emergencies, fuel-rich combustion might provide a small amount of extra thrust with existing afterburner equipment. At most, fuel-rich afterburning would require a second afterburner fuel system and an exhaust nozzle capable of greater area changes.

Rich combustion of a given weight of either hydrogen or hydrazine (added to a stoichiometric mixture of hydrogen and air) can yield higher net thrusts than diborane. When fuel volume is critical, fuel-rich afterburning with hydrazine addition should be considered.

Net-thrust values for fuel-rich combustion can be raised by heating the fuel with energy sources external to the engine. Fuel-rich afterburning of 700° K hydrogen can produce thrusts 30 pounds per pound of air per second greater than those for stoichiometric combustion of hydrogen at 700° K and 400° K air augmented with a 321.6-second specific-impulse rocket. Net thrusts for complete expansion from 1 to 0.0909 atmosphere of 700° K hydrogen are equal to those for a 321.6-second specific-impulse rocket.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, April 22, 1957

APPENDIX - SYMBOLS

A	area per unit of weight flow rate of air
a	weight flow rate of air
F_n	net thrust per unit of weight flow rate of air
f	weight flow rate of fuel
g	gravitational constant
H_T^O	enthalpy per mole at temperature T and pressure of 1 atm
ΔH	total enthalpy change
J	constant for conversion of work units to heat or enthalpy units
M	molecular weight
m	exhaust-nozzle-exit stream momentum per unit of weight flow of air
n	number of moles
p	pressure (static)
R	universal gas constant
S_a	air specific impulse
S_T^O	entropy per mole at temperature T and pressure of 1 atm
T	temperature (static)
V	velocity

Subscripts:

am	ambient
c	afterburner combustion conditions (zero velocity)
EP	afterburner exhaust products
e	nozzle-exit conditions
f+a	fuel plus air at inlet conditions
g	gaseous components
i	i^{th} constituent

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TABLE I. - AFTERBURNER-INLET CONDITIONS FOR VARIOUS TURBOJET

ENGINES AND AMBIENT CONDITIONS

[Ref. 2.]

Engine type	Compressor pressure ratio	Altitude, ft	Flight Mach number	Engine-inlet total temperature, °R	Afterburner-inlet total temperature, °R	Primary-combustor combustion efficiency	Ratio of afterburner-inlet total to ambient static pressures	Afterburner-inlet Mach number
A	5.2	0	0	519	1760	0.99	1.98	0.205
		50,000	.81	445	1760	.97	3.25	.209
B	7.8	0	0	519	1670	0.99	2.30	0.220
		50,000	.81	445	1670	.97	3.87	.218
C	12	0	0	519	1510	0.98	2.24	0.185
		50,000	.81	445	1510	.96	4.28	.190
D	8.4	0	0	519	2062	0.99	2.60	0.222
		50,000	.81	445	2110	.98	4.90	.200
			.90	457	2104	.98	5.30	.204
			1.27	520	2062	.985	7.16	.222
			1.534	578	2026	.99	8.94	.236
			2.025	715	1995	.99	13.07	.249
			2.37	835	1989	.99	16.92	.252
			2.50	884	2001	.99	19.04	.246

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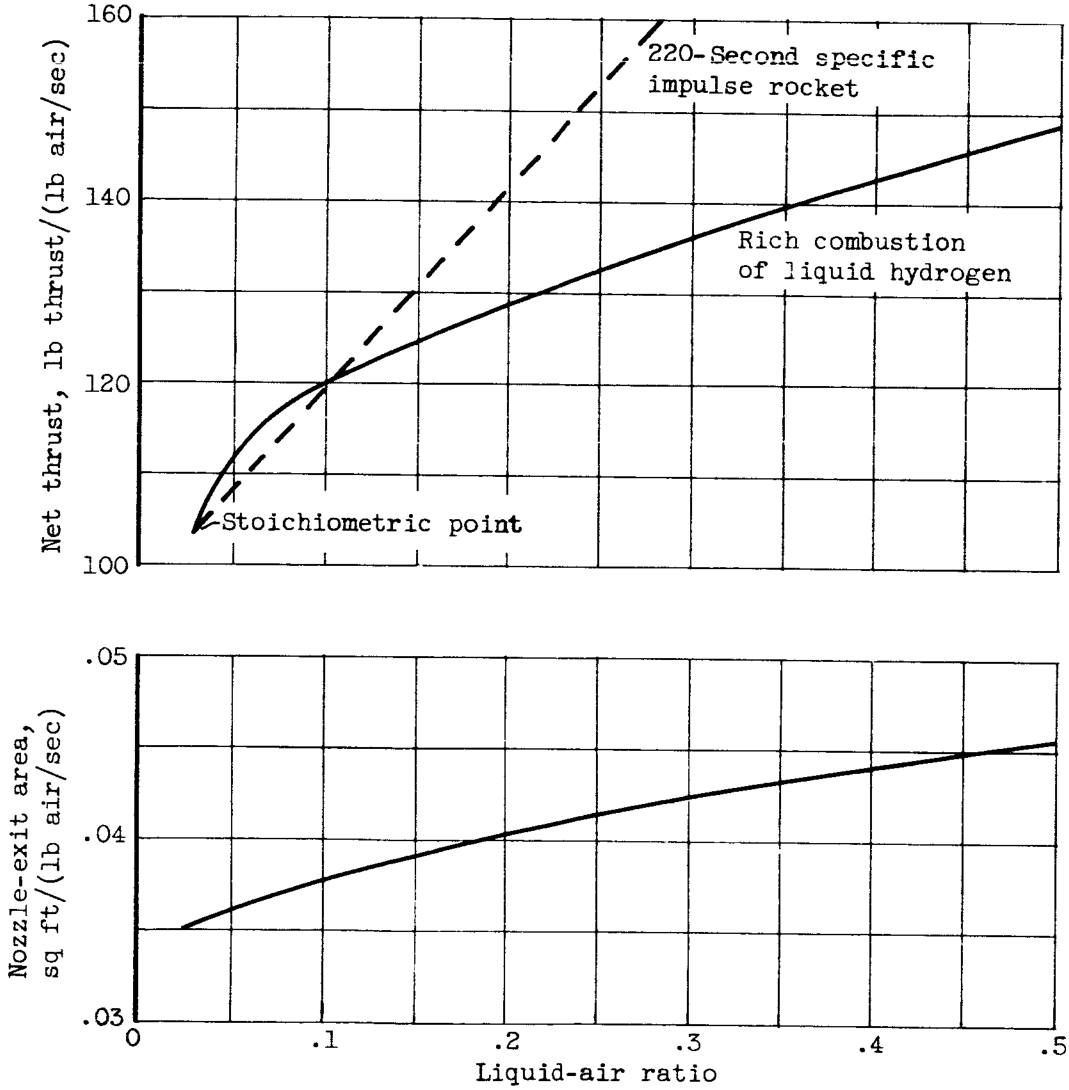

(a) Liquid hydrogen at 20.39° K.

Figure 1. - Variations of net thrust and exhaust-nozzle-exit area with liquid-air ratio for complete frozen-composition expansion from 2 to 1 atmosphere of rich-combustion products at sea-level static conditions. Inlet-air temperature, 298.16° K.

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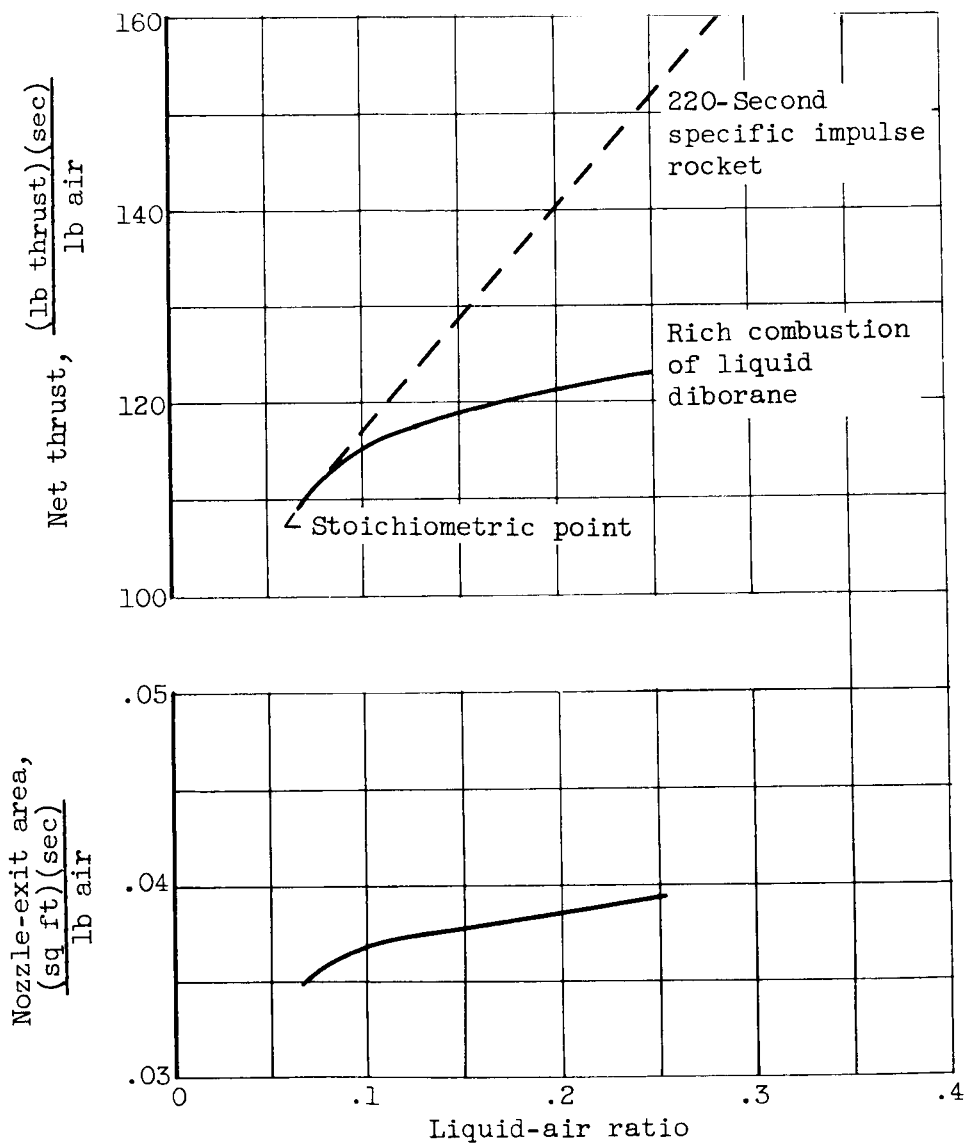

(b) Liquid diborane at 180.63° K.

Figure 1. - Continued. Variations of net thrust and exhaust-nozzle-exit area with liquid-air ratio for complete frozen-composition expansion from 2 to 1 atmosphere of rich-combustion products at sea-level static conditions. Inlet-air temperature, 298.16° K.

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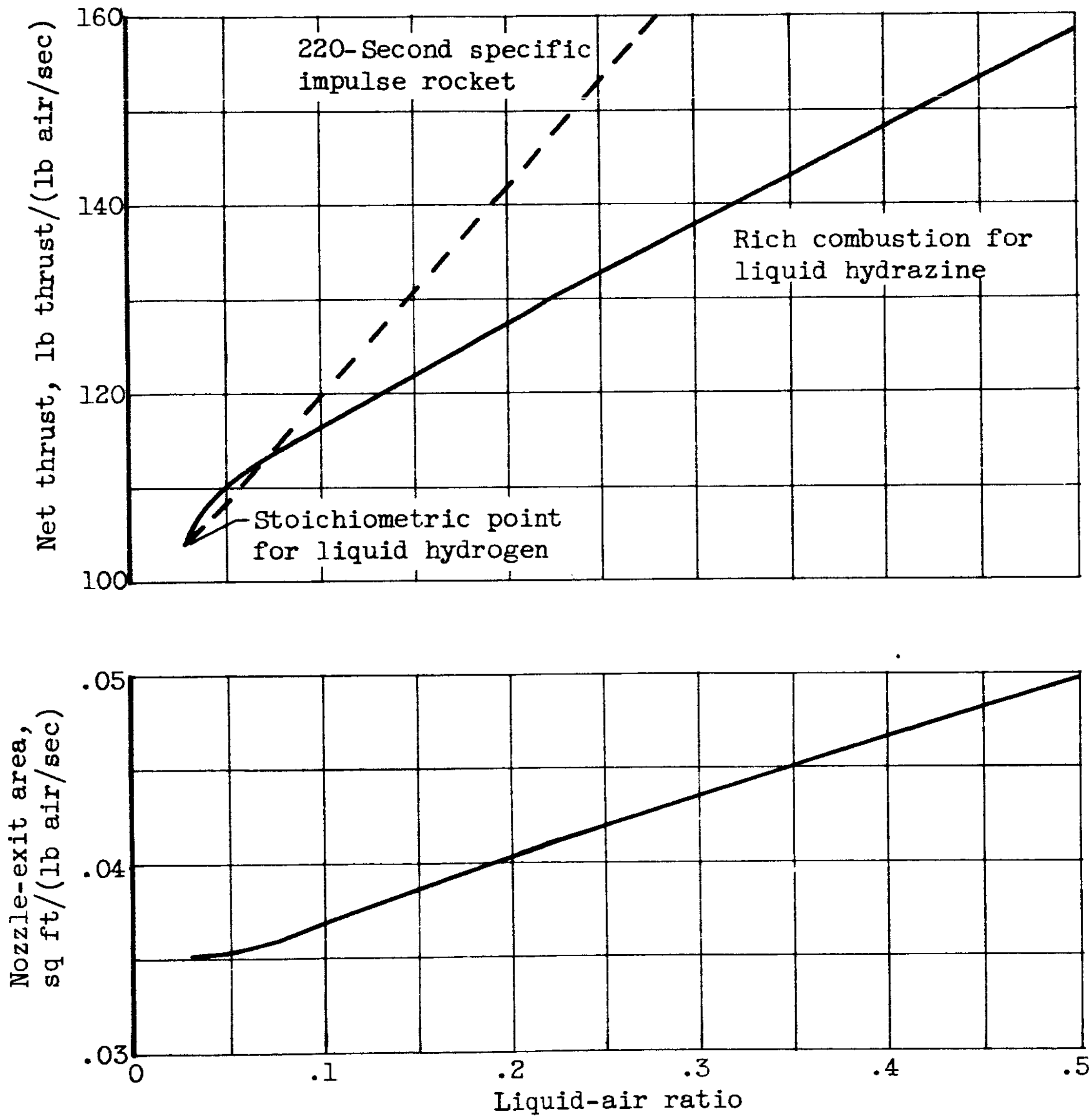

(c) Liquid hydrazine at 298.16° K and stoichiometric mixture of liquid hydrogen at 20.39° K and air.

Figure 1. - Concluded. Variations of net thrust and exhaust-nozzle-exit area with liquid-air ratio for complete frozen-composition expansion from 2 to 1 atmosphere of rich-combustion products at sea-level static conditions. Inlet-air temperature, 298.16° K.

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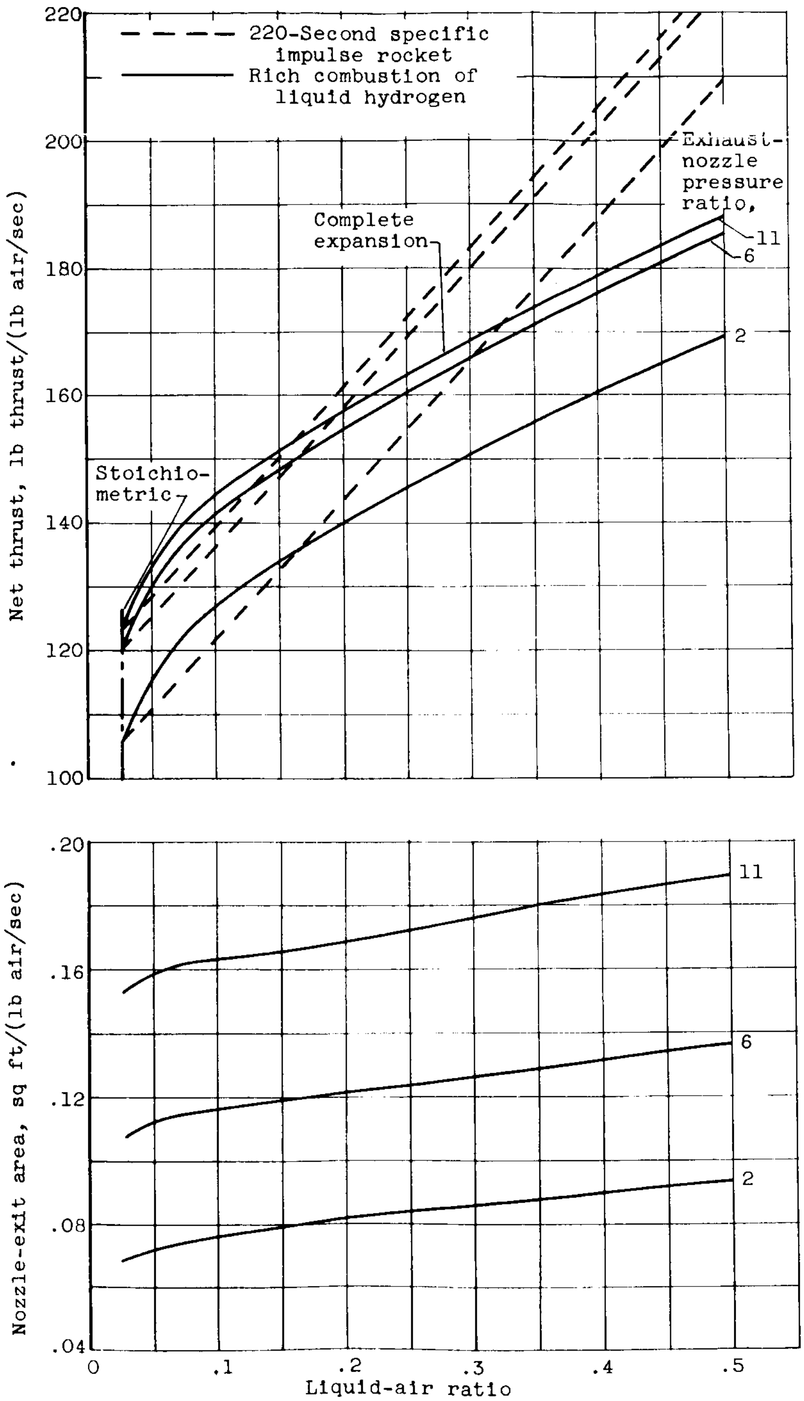

(a) Liquid hydrogen at 20.39° K.

Figure 2. - Variations of net thrust and exhaust-nozzle-exit area with liquid-air ratio and exhaust-nozzle pressure ratio for frozen-composition expansion from 1 atmosphere of rich-combustion products at flight conditions. Mach number, 2; altitude, 55,000 feet; inlet-air temperature, 400° K.

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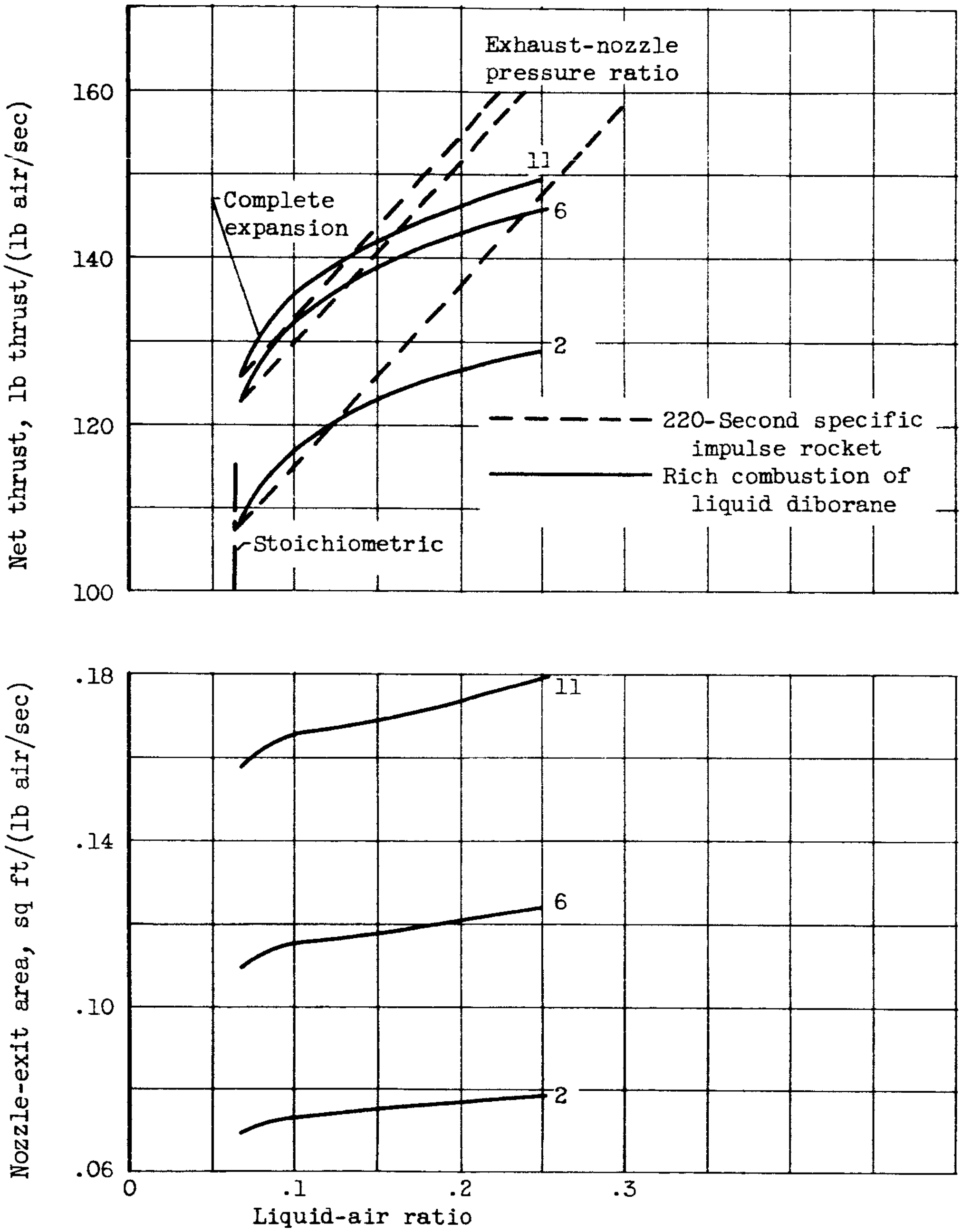

(b) Liquid diborane at 180.63° K.

Figure 2. - Continued. Variations of net thrust and exhaust-nozzle-exit area with liquid-air ratio and exhaust-nozzle pressure ratio for frozen-composition expansion from 1 atmosphere of rich-combustion products at flight conditions. Mach number, 2; altitude, 55,000 feet; inlet-air temperature, 400° K.

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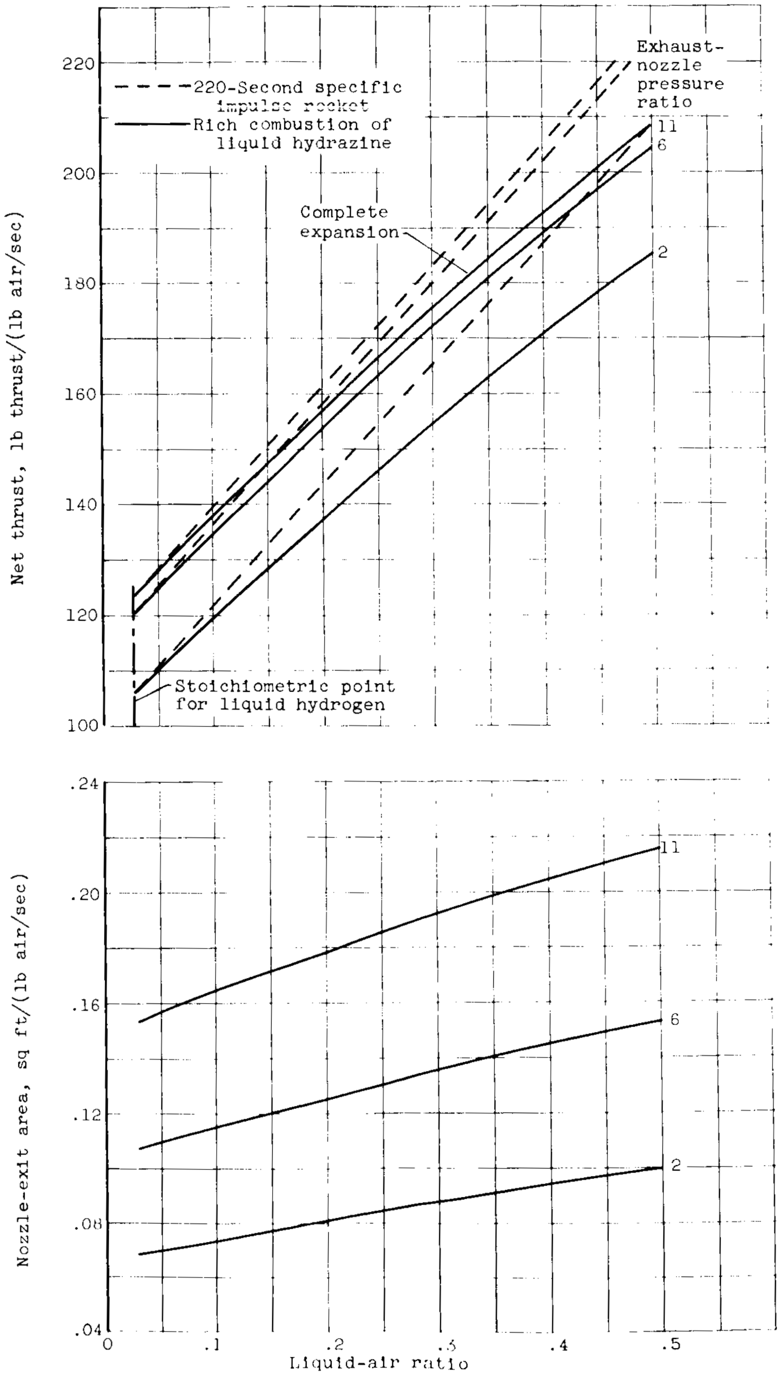

(c) Liquid hydrogen at 298.16° K and a stoichiometric mixture of liquid hydrazine at 20.39° K and air.

Figure 2. - Concluded. Variations of net thrust and exhaust-nozzle-exit area with liquid-air ratio and exhaust-nozzle pressure ratio for frozen-composition expansion from 1 atmosphere of rich-combustion products at flight conditions. Mach number, 2; altitude, 55,000 feet; inlet-air temperature, 400° K.

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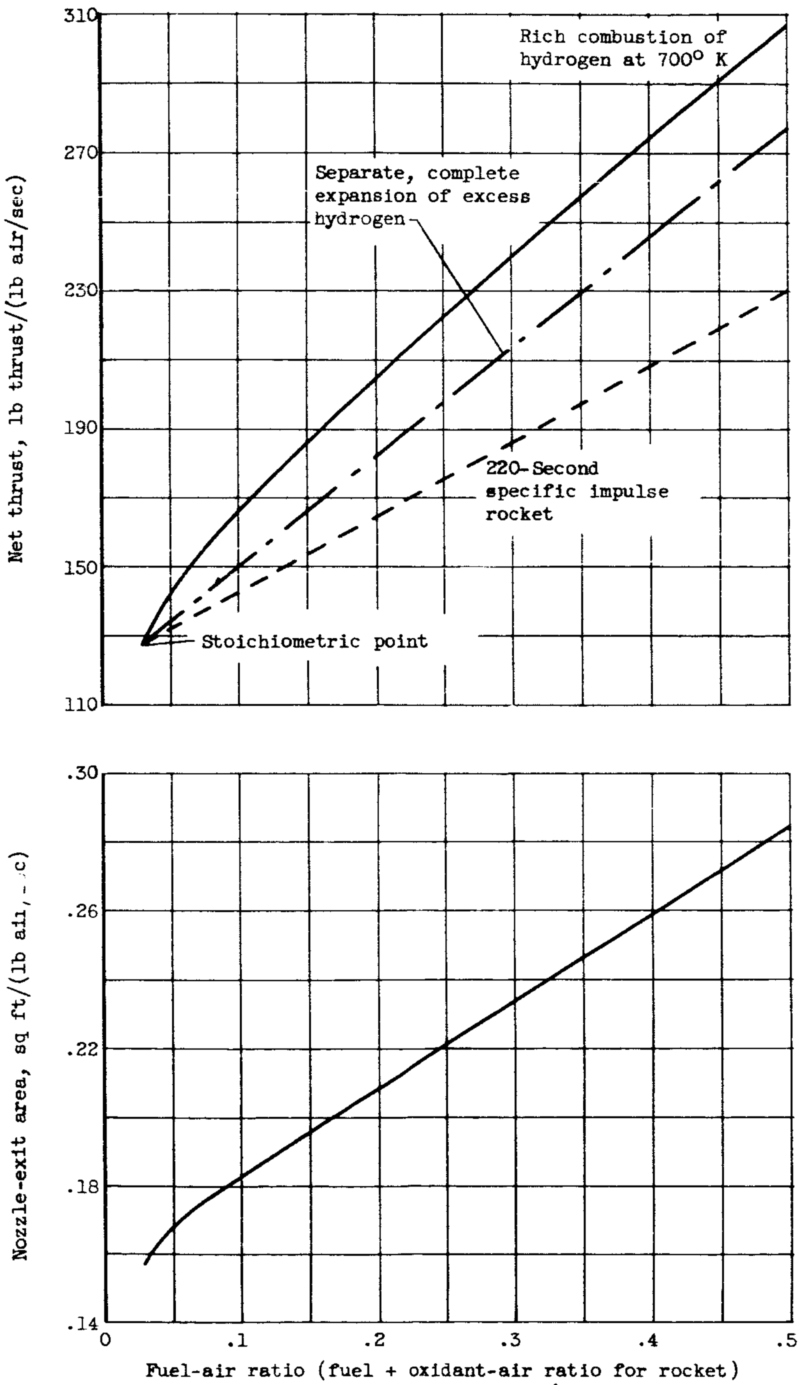

Figure 3. - Variation of net thrust and exhaust-nozzle-exit area with fuel-air ratio for complete, frozen-composition expansion from 1 to 0.0909 atmosphere of rich-combustion products for gaseous hydrogen at 700° K at flight conditions. Mach number, 2; altitude, 55,000 feet; inlet-air temperature, 400° K.